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Service support system modelling language for simulation-driven development of functional products

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Abstract

A functional product (FP) comprises of an integrated package of hardware and support services sold under a performance-based contract. A barrier to the adoption of FP is the lack of tools for obtaining predictions of availability and support costs during product development. A previous paper by the authors described a simulation-driven development strategy for designing FP that are optimised for functional availability and support costs. This iterative strategy involves representing the FP design in a modelling language; using a software code to automatically generate and analyse a simulation model from this representation to produce detailed performance predictions; and using these predictions as feedback to improve the design. The use of a modelling language facilitates the representation of the design details within the hardware and support system that influence availability and support costs. This includes the maintenance process design, maintenance strategy design and maintenance resource availability design. In this paper, an overview of a modelling language the authors have developed for this purpose is described.

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Keywords: Functional products, simulation modelling, service support system, modelling language.

1. Introduction

A functional product (FP) [1] is a form of product service system (PSS) where the product function is sold under a performance based contract such that the supplier retains ownership of the hardware and the supplier's compensation is tied to the value that the product generates for the customer [2]. They consist of an integrated package combining hardware and a service support system. FP sales are most suitable when the product has high cost and complexity, requires significant maintenance provision and provides a function that is crucial to customer operations such that high functional availability (defined as the proportion of uptime [3]) is critical. An example is the 'power-by-the-hour' scheme offered by Rolls-Royce PLC for the supply of gas turbine engines to airlines. A previous paper [4] by the authors described a high-level strategy for the development and optimisation of a FP design for availability and availability support costs. The strategy involves describing the product design in a modelling language, the use of simulation modelling to derive the performance of the products sold over their contract lifetimes and analysis of that performance to provide benchmarking and decision support for design changes (see Figure 1). A modelling language can be defined as a formal notation, which may be textual or graphical, used to express information or knowledge or systems in a structure that is defined by a consistent set of rules. This paper presents a modelling language that has been developed by the authors for representing the design of an FP, in particular its service support system. The primary motivation for its development was to enable the second step in the strategy for the development of optimised FP designs (shown in Figure 1) to be performed.

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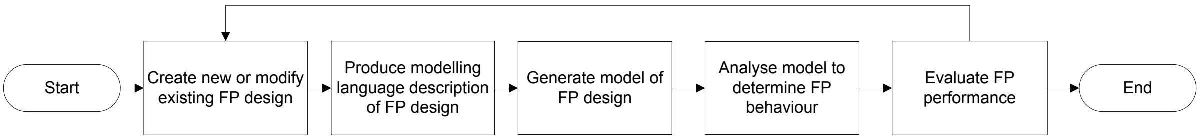

Fig. 1. A strategy for the development of a FP design.

1.1. Related work in the area of service support system modelling

Many domain specific modelling languages have been developed, such as SysML [5] for systems engineering and IDEF0 [6] for integrated computer aided manufacturing. However, existing modelling languages for the description of a service support system are lacking in the literature, although some previous work exists in the area of general service modelling. Morelli carried out an exploration of methodologies and tools for the design of PSS [7] and stated that one of the main questions designers of PSS have to face is “How can designers represent material and immaterial components of PSS? While products are easily represented through technical drawings, there are not many metaphors and graphical tools available to represent the immaterial component in services and the relationship between material and immaterial elements of a product / service system.” Morelli then proposed methods for representing the structure of PSS [8] but this was approached from a design blueprinting perspective rather than for deriving performance predictions through modelling of the design. Kimita et al [9] proposed a method for analysing the cost of a general service involving blueprinting the design and then building a simulation model of the cost driver activities. Watanabe et al [10] presented a method for representing a service in terms of its relation to various stakeholders and a method for generating a simulation model from this representation that can be used to analyse its impact on these stakeholders. Li and Thompson [11, 12] reviewed research on concepts and models for service reliability in a range of applications, studied the characteristics of a service support system within a FP and developed a modelling and simulation approach to provide support during service design. The modelling approach is limited to simple maintenance process reliability modelling and does not extend to the modelling of a complete service support system or its interaction with supported hardware items. Reed et al [13] a developed a method for modelling simple maintenance processes within an integrated FP model. Löfstrand et al [14] presented a model for how to integrate monitoring (of industrial systems) with approaches for predicting industrial system availability using simulation.

1.2. New Modelling Language

The authors have developed a new modeling language for the representation of FP designs including the service support system element. It has been designed to be executable in the sense that a software tool can be written (such as the tool that has been developed by the authors) to form a model of a FP from its modelling language description and produce predictions for product performance (such as functional availability and support costs). As such it is has been developed with precise and formal rules that eliminate ambiguities. It also has a modular design such that each aspect of the FP design is described separately. The benefits of the modular approach are twofold:

- It enables the descriptions of the different areas of the design to be produced separately by the relevant persons.
- A FP may have specialised design features in one area that cannot be described using the standard modelling language. In these cases, the modelling language can be adapted or a custom modelling language developed for that specific design area whilst the standard modelling language can be used elsewhere without modification.

The main focus of this paper is to describe the new modeling language with respect to the representation of a service support system design.

2. Overview of service support systems in functional products

The service support system within a FP consists of all the services provided by the supplier for the support and delivery of the function sold to customers. A major function of the service support system, and the element that directly impacts functional availability and availability support costs, is the application of maintenance processes. Maintenance processes apply resources to hardware items through a series of tasks in order to modify, or reveal through inspection, the reliability state of some of those items (e.g. to transition a hardware item from a worn to ‘as-new’ condition state or to determine whether a hardware item is in a particular failure mode state). The hardware items acted on by a maintenance process includes those within the operational products and spare parts sourced from inventory. The design of a maintenance process within a service support system will dictate the time it takes to complete and the maintenance resource occupation and usage, thus impacting both on functional availability and support costs for the FP. The set of rules that define when (i.e. under which conditions) and which maintenance processes are applied to the various components and sub-systems within the hardware form the maintenance strategy. The hierarchy in Figure 2 summarises the types of maintenance triggers that may be utilised within a maintenance strategy. The top level categories in the hierarchy are corrective maintenance, where maintenance processes are applied to hardware when it fails, and preventive maintenance, where maintenance processes are applied to hardware prior to it failing. The maintenance strategy design is a key area of the overall service support system design since applying the right maintenance processes to the right hardware items at the right time is critical to attaining the optimal functional availability and support costs within an FP.

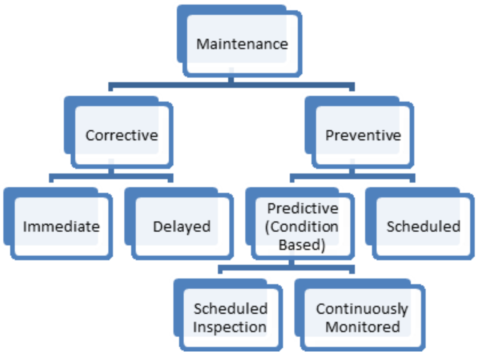

Fig. 2. Hierarchy of different maintenance triggers.

The resources applied within maintenance processes include human resources, tools, facilities and spare hardware items. There may be numerous locations within a service support system where resources may be located and where maintenance may be performed such as customer sites, support bases and spare parts storage facilities. In general, hardware items are transferable between locations whilst other resources, such as workshop facilities, are non-transferable and thus of fixed availability at a given location. In addition to the movement of hardware items between locations within the support network, they may enter the network from external suppliers or exit the network through scrapping (e.g. a failed hardware item that has been replaced and for which repair is not economically viable). A maintenance task may be delayed whilst either waiting for an occupied fixed location resource to become free or for a transferable resource to arrive at the location at which the task is carried out. An important element of the service support system design therefore consists of the choice of resource locations, how many of each fixed resource are made available at each location and the logistical system for the availability and movement of hardware items between locations at which maintenance is performed.

3. Modelling language for representing service support system design

The modelling language for representing the service support system design consists of a modular set of notations to describe the maintenance processes, maintenance resources and maintenance strategy. Although not the main focus of the paper, it is necessary to begin with an overview of how the other element of an FP, the hardware systems, is described in the modeling language. This is required since the service support system and hardware within an FP are highly integrated.

3.1. Overview of hardware modelling language description

Hardware component types (i.e. of a given specification) are described in terms of:

- A reliability model consisting of the set of reliability states (e.g. working and presence of failure modes) and transitions. Additionally, reliability states may be marked as unrevealed if entry to that state remains hidden until an inspection is performed.
- A configuration model consisting of the set of configuration attributes (e.g. power supply status) and, for each attribute, the set of possible configuration states (e.g. connected and disconnected). Additionally, the default configuration states for the hardware item when operational and stored in spares inventory must be stated.

Systems are described in terms of the hierarchy of components and sub-system types from which they are formed (these may be installed or uninstalled during maintenance), any cross-hierarchical relations between items within a system and the reliability structure of the system.

3.2. Maintenance processes

Maintenance processes are represented as the flow of hardware items through maintenance tasks, where these tasks alter the reliability or configuration state of the hardware items and may have maintenance resources other than hardware items applied as inputs and released as outputs. The structure of a generic maintenance task is shown in Figure 3.

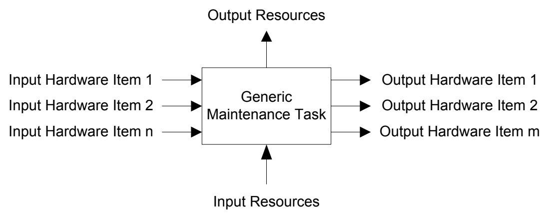

Fig. 3. Structure of a generic maintenance task.

The following types of maintenance task are defined in the modelling language:

- Disassembly / Sub-Item Removal – single hardware system item input and multiple hardware item outputs comprising of items from that system. E.g. the removal of an electric motor from within the power unit assembly of a hydraulic drive system.
- Assembly / Sub-Item Installation – multiple hardware item inputs and single hardware system item output comprised from the input items. E.g. the installation of an electric motor within the power unit assembly of a hydraulic drive system.
- Configuration attribute transition – same single hardware item input and output with the specification of a configuration attribute transition for that item. E.g. the removal of the maintenance access window cover from the power unit of a hydraulic drive system.
- Component reliability state transition (e.g. restoration) - same single hardware item input and output with the

specification of a reliability state transition for that item. E.g. the rewinding of the electric motor from a hydraulic drive system.
- Null – no hardware item inputs or outputs but has resource inputs. E.g. the completion of maintenance documentation.
- Inspection - same single hardware item input and output with the specification of the reliability state from that item for which state is revealed. E.g. determine the wear state of a bearing from the electric motor from a hydraulic drive system.

An example of the modeling language representation of a maintenance task for the removal of a drive gear from a gear pump is shown in Figure 4.

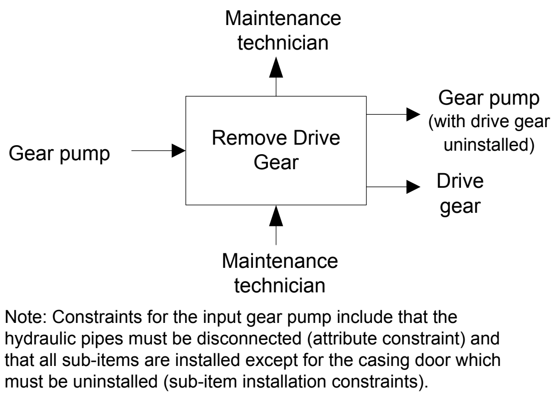

Fig. 4. Example of a maintenance task for the removal of the drive gear from a gear pump (disassembly task).

The input hardware items consist of both the maintained hardware and spare parts, the latter of which must be sourced and may be subject to a logistical delay if they are not immediately available at the location where maintenance is performed. The output hardware items may flow to subsequent maintenance tasks for further processing, returned to inventory for later reuse (e.g. a replaced item that has been reconditioned), transferred to another maintenance location (e.g. for off-site maintenance processing) or scrapped (e.g. where the cost of repairing a replaced failed item is deemed uneconomical). These choices are indicated by the destination of the output arrows from the maintenance task in the maintenance process representation. The input maintenance resources are sourced from the maintenance location and a logistical delay may occur if the required resources are not immediately available due to being occupied by other concurrently performed maintenance from the same or other maintenance processes. The greater importance given to completing certain maintenance processes and tasks that are competing for scarce maintenance resources, and hence precedence in resource allocation, is denoted by assigning them priorities within the modeling language. Task priorities are denoted for each task in the maintenance process representation, whilst maintenance process priorities are defined within the maintenance strategy representation.

Each maintenance task is also associated with a completion time distribution that represents the time between the set of input hardware items and other resources being acquired for the task and the completion of the task and associated output of hardware items and resources. Finally, each task may specify constraints for the input hardware items that give the acceptable configuration states (e.g. a maintenance task for a gas turbine engine might specify that maintenance access panel C must be in the open state) and installed status of sub-items (e.g. that the engine diagnostic unit is installed in the gas turbine engine). The specification of these constraints and the configuration attribute state transitions for each maintenance task, along with the operational and spares inventory default states for each hardware item, enable constraint verification to be performed which can help with the design of maintenance procedures during product development.

3.3. Maintenance strategy

A comprehensive formal syntax has been developed for the precise expression of the rules applied within a maintenance strategy, which take the basic form of "FOR hardware item IF condition met THEN PERFORM maintenance response ON hardware item". A simplified example for a preventative scheduled maintenance rule is "FOR pump IF age exceeds 15000 operating hours THEN replace bearing ON pump rear bearing". The syntax enables generalised rules to be stated that apply to multiple hardware items (usually of the same or similar specification) and is designed so that complex maintenance strategies can be stated precisely and concisely.

3.4. Maintenance resources

The modelling language representation for the logistical system network topology takes the form of a directed graph where nodes represent locations and edges represent the time (or time distribution if random variations are significant) for the transfer of spare hardware items between the connected nodes. The graph may take the form of a multigraph where multiple edges are incident between the same nodes to represent differences in transfer times for hardware items of different types. A formal syntax has been developed to represent the rules that dictate when a transfer of spare hardware items is initiated between locations. This syntax can be used to describe both push and pull actions. Each location node is associated with its set of transfer rules. Note that only major high cost spare part items need to be included within the modelling language representation of a service support system since low cost items should always be immediately available (due to the very high relative cost of logistical delays that may increase downtime). However, the costs of such items should be accounted for during the post-simulation modelling analysis stage in order to establish the total support costs.

4. Simulation modelling tool

The authors have developed a software tool, written for the .NET software framework in the C# programming language, that generates a discrete event simulation model of an FP from the representation of its design in the modelling language. Simulation trials can be generated from this model, each consisting of a vast sequence of events (e.g. hardware failures, maintenance task executions and maintenance resource demands) that correspond to a possible operational outcome scenario for the modelled FP. The data generated from a large number of trials, possibly combined with auxiliary data (such as maintenance resource costs), can then be analysed to calculate a wide range of metrics to support decisions during product development. A hierarchy containing some of the metrics that can be obtained was given in a previous paper [4]. For example, the expected support costs and support cost distribution (see the example in Figure 5) for an FP design can be derived.

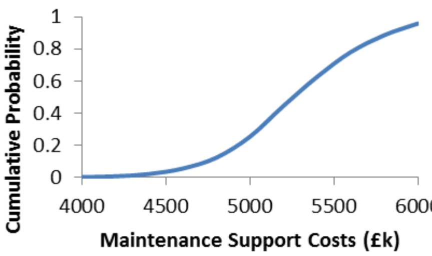

Fig. 5. The support cost distribution for an FP design that was derived from a simulation model generated from its modelling language representation.

5. Conclusion

The ability to accurately predict the performance, in terms of functional availability and support costs, of a FP design through modelling is very useful during product development, enabling the implementation of an iterative development strategy where feedback on design choices is provided by analysis of the model output. In order to generate such a model for a particular FP, a representation of the structure and details of the hardware and the service support system design is required. A review of the literature showed that whilst research has begun in the area of modelling PSS, suitable methods for this purpose are still lacking. An overview of the modelling language that has been developed by the authors to meet this need has been described. Comprising of both graphical and textual notations, it permits the detailed and unambiguous description of both hardware and service support system design within an FP. The modelling language and corresponding modelling software are continuing to be developed by the authors and its application to real systems is particularly important in order to discover areas for improvement, refinement, extension and generalisation that can increase its practical value. A set of graphical user interfaces (GUIs) for creating FP design representations in the modelling language are also under development by the authors. These will enable rapid input of the initial modelling language representation of a FP design as well as later modifications resulting from implemented or proposed design changes, thus supporting the proposed iterative simulation-driven product development strategy.

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